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Electrostatic Ion Instabilities in the Presence of Parallel Currents and Transverse Electric Fields

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The electrostatic ion instabilities are studied for oblique propagation in the presence of magnetic field-aligned currents and transverse localized electric fields in a weakly collisional plasma. It is shown that the presence of transverse electric fields may result in mode excitation for the magnetic field aligned current values that are otherwise stable. The electron collisions enhance the growth while ion collisions have a damping effect. These results are discussed in the context of observations of low frequency ion modes in the auroral ionosphere by radar and rocket experiments.

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CONTENTS

ELECTROSTATIC ION INSTABILITIES IN THE PRESENCE OF PARALLEL CURRENTS AND TRANSVERSE ELECTRIC FIELDS

1. INTRODUCTION

It is well known that an equilibrium current parallel to the magnetic field may lead to the excitation of obliquely propagating electrostatic ion modes in a plasma, such as the ion-cyclotron (EIC) mode in the collisionless [Drummond and Rosenbluth, 1962; Kindel and Kennel, 1971] and in collisional limits [Milic, 1972; Chaturvedi and Kaw, 1975] and ion acoustic waves [Chaturvedi et al., 1987]. These instabilities have been extensively studied in the context of the auroral ionosphere [Kindel and Kennel, 1971; D'Angelo, 1973; Chaturvedi, 1976; Satyanarayana et al., 1981; Providakes et al., 1985; Chaturvedi et al., 1987]. Radar observations [Fejer et al., 1984; Haldoupis et al., 1985; Villain et al., 1987] and in-situ rocket measurements [Kelley et al., 1975; Ogawa et al., 1981; Yau et al., 1983; Bering, 1984] have detected these waves in the auroral ionosphere. It has been shown by Kindel and Kennel [1971] that the EIC instability has the lowest threshold of excitation among the various current driven ion instabilities for the topside ionosphere. Thus, these observations have been interpreted as the modes excited by field-aligned currents (FAC). Often however, along with the FAC, transverse d.c. electric fields have also been observed [Fejer et al., 1984; Providakes et al., 1985], and the threshold values for excitation by FAC alone are likely to be exceeded only during periods of strong geomagnetic activity [Providakes et al., 1985; Chaturvedi et al., 1987].

Recently, it has been demonstrated that the presence of transverse localized electric (TLE) fields can result in the excitation of electrostatic ion modes [Ganguli et al., 1985a, 1985b, 1988]. These modes have recently been seen in PIC simulations conducted by Nishikawa et al. [1987]. This nonlocal instability is a result of coupling between the negative-energy wave in the localized electric field region with the positive energy wave outside it. These studies were for collisionless plasmas and largely for $k_\perp \gg k_\parallel$ waves: but the important role of the TLE fields in a realistic study of the low-frequency ion-wave excitation in the auroral ionosphere was demonstrated. In this paper, we study the combined effects of a TLE field and an FAC on the stability of the ion-modes. We also include the electron neutral (ν_{en}) and the ion neutral (ν_{in}) collisions. We find that the inclusion of TLE field can have notable effects on the dispersive characteristics of the ion-modes. For example, the real frequency of the unstable modes can have values,

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depending on parameters such as the TLE field strength, that vary from below Ω_i to values greater than Ω_i, the ion cyclotron frequency. More importantly, we find that the mode excitation may occur for sub-threshold parallel current (electron drift) values when the TLE field is included. These results may be of interest for the ion wave observations in auroral ionosphere, especially for those observations where it appears that the ambient conditions set the threshold value of the parallel current for excitation of the ion waves above the level that one might expect to be attainable under normal circumstances. A combination of a parallel current and a TLE field can lead to excitations of the ion waves under much less severe conditions.

2. THEORY

We wish to study the stability properties of a weakly ionized collisional plasma which is typical of the auroral ionosphere, characterized by an equilibrium current flowing parallel to the ambient magnetic field and a localized transverse d.c. electric field (see figure 1). We describe the particle dynamics by using the Vlasov equation with a BGK-type of model relaxation collision term. The equilibrium current is predominantly carried by thermal electrons drifting along the magnetic field, $B_0\hat{z}$, with a drift velocity, $V_d\hat{z}$. The transverse d.c. electric field, $E_0(x)$, is localized along the x-axis to a distance L_v and is piecewise continuous. Thus, the ions and electrons both have an equilibrium cross-field drift ($V_0\hat{y}$, $V_0 = -cE_0/B_0$), which is also localized in the x-direction to the distance L_v. In reality, however, the profile of V_0 is no longer of the square hat shape and is rather smooth due to the finite-Larmor-radius (FLR) effects at the boundaries of the electric field region. For simplicity we shall use a sharp profile for V_0 in the present study, and shall subsequently relax this condition in the future. A similar approach was taken in developing the collisionless TLE only theory [Ganguli et al. 1985a, 1985b, 1988], where it was found that the transition from the idealized square hat profile to a more self consistent smooth profile resulted in quantitative but not qualitative changes in the theoretical predictions. The effects associated with the Hall and the Pederson mobilities are small for weak collisions, especially when the velocity shear is weak; and are therefore neglected. Our treatment is general in as much as it includes collisions and thus is appropriate for

low-altitude applications; and, at the same time, the collisionless results (applicable at higher altitudes) can be readily obtained by setting the collision frequencies to zero.

The dispersion properties of the collisional ion cyclotron modes in the local limit and in the absence of a d.c. electric field are described by the relation

$$1 + \varepsilon_i + \varepsilon_e = 0 \qquad (1)$$

where expression for $\varepsilon_j (j \equiv e, i)$ is given as [Clemmow and Dougherty, 1969; Kindel and Kennel, 1971]

$$\varepsilon_j = \frac{\sum_{n=-\infty}^{+\infty} \left[\Gamma_n(\mu_j)/k^2\lambda_{Dj}^2\right]\left\{1 + \left(\tilde{\omega}_j/k_{\parallel}v_{tj}\right)Z\left[\left(\tilde{\omega}_j + n\Omega_j\right)/k_{\parallel}v_{tj}\right]\right\}}{1 + i\left(\nu_j/k_{\parallel}v_{tj}\right)\sum_{n=-\infty}^{\infty} \Gamma_n(\mu_j)Z\left[\left(\tilde{\omega}_j + n\Omega_j\right)/k_{\parallel}v_{tj}\right]} \qquad (2)$$

The notations used here are standard: n refers to the harmonic number; $\tilde{\omega}_j = \omega + i\nu_j$ where ω is the complex eigenfrequency, $\omega = \omega_r + i\gamma$; $\lambda_{Dj} = (T_j/4\Pi n_j e^2)^{1/2}$ is the Debye length of the species; and T_j, n_j and m_j are respectively temperature (in energy units), number density and mass of the species j; $v_j = (2T_j/m_j)^{1/2}$ is the species thermal velocity; ν_j their collision frequency with neutrals; $\rho_j = v_j/\Omega_j$, the gyroradius; $\Gamma_n = I_n \exp(-b_j)$, where I_n is the modified Bessel function of order n; $b_j = k_\perp^2 \rho_j^2/2$; and $Z(\zeta_j)$ is the plasma dispersion function [Book, 1986].

We now introduce a localized transverse d.c. electric field (see figure 1). This modifies the dispersion relation. Region I ($|x| < L_v/2$), over which the electric field is localized, is characterized by $E_0 = E_0\hat{x}$; $V_{0\perp} = V_0\hat{y}$; $\tilde{\omega}_i = \omega_1 + i\nu_i$; $\tilde{\omega}_e = \omega_1 + i\nu_e - k_z V_d$. In region II we have $E_0 = 0$; $V_{0\perp} = 0$; $\tilde{\omega}_i = \omega + i\nu_i$; $\tilde{\omega}_e = \omega + i\nu_e - k_z V_d$. Here $\omega_1 = \omega - k_y V_0$.

We shall assume that the density gradient is negligible. Strictly speaking, the parallel current is also of finite width in the x-direction. The typical scalelength of this width, L_c, is assumed to be either $L_c > L_v$ or $L_c = L_v$. We discuss implications of these inequalities in the discussion section. For a more rigorous description of the equilibrium we refer to Ganguli et al. (1988).

We follow the approach adopted by Ganguli et al. [1985a] in deriving the nonlocal dispersion relation. We use the quasi-neutrality assumption ($\varepsilon_e + \varepsilon_i \simeq 0$). As a result of the x-dependence of the equilibrium the perturbed quantities cannot be Fourier transformed in x. Instead we obtain a differential equation in x. For the specific profile of the electric field under consideration (see figure 1), the modes are described by

$$\left(\frac{\partial^2}{\partial \xi^2} + \kappa_I^{\,2}\right) \Phi_I(\xi) = 0 \qquad \text{, for Region I} \tag{4}$$

and

$$\left(\frac{\partial^2}{\partial \xi^2} + \kappa_{II}^{\,2}\right) \Phi_{II}(\xi) = 0 \qquad \text{, for Region II} \tag{5}$$

where $\xi = x/\rho_i$ and $\kappa_I^{\,2} = Q_I/A_I$ and

$$Q_I = C\left\{1 + \sum_n \Gamma_n \left(\tilde{\omega}_i/k_{\parallel}v_i\right) Z\left(\frac{\tilde{\omega}_i + n\Omega_i}{k_{\parallel}v_i}\right)\right\}$$

$$+ \tau D\left\{1 + i\left(\nu_i/k_{\parallel}v_i\right) \sum_n \Gamma_n \, Z\left(\frac{\tilde{\omega}_i + n\Omega_i}{k_{\parallel}v_i}\right)\right\} \tag{6}$$

$$A_I = -\frac{1}{2}\left[C\left\{\sum_n \Gamma_n' \left(i\nu_i / k_{\parallel}v_i\right) Z\left(\frac{\tilde{\omega}_i + n\Omega_i}{k_{\parallel}v_i}\right)\right\}\right.$$

$$\left. + \tau D\left\{\sum_n \Gamma_n' \left(i\nu_i/k_{\parallel}v_i\right) Z\left(\frac{\tilde{\omega}_i + n\Omega_i}{k_{\parallel}v_i}\right)\right\}\right] \tag{7}$$

$$C = \left\{1 + i\left(\nu_e/k_{\parallel}v_e\right)Z\left(\tilde{\omega}_e/k_{\parallel}v_e\right)\right\} \; ; \; D = \left\{1 + \left(\tilde{\omega}_e/k_{\parallel}v_e\right)Z\left(\tilde{\omega}_e/k_{\parallel}v_e\right)\right\}$$

Only the n = 0 harmonic for the electrons is considered and $\Gamma_n' = \partial\Gamma_n/\partial b$.

In the above, $\tau = T_i/T_e$, and κ_{II} is obtained by setting $V_0 = 0$ in κ_I. The nonlocal dispersion relation for the even modes obtained by matching the logarithmic derivatives of the solutions of (4) and (5) at $x=L_v/2$ (for details see Ganguli et al. [1985a]) is given by,

$$- \kappa_I \tan (\kappa_I/2\varepsilon) = i \kappa_{II} \tag{9}$$

where $\varepsilon = \rho_i/L_v$. A similar relation can also be obtained for the odd modes.

The well-known limits of (9) are straightforward to obtain. In the local approximation, and for $E_0 = 0$, we recover the current driven EIC instability in the collisionless ($\nu_j=0$) and the collisional ($\nu_j\neq0$) limits. Further, for $\nu_j = 0$ and $V_d = 0$, (9) reduces to the dispersion relation given by Ganguli et al. [1985a] to yield an electrostatic ion-instability.

Here we study the combined effects of the two aforementioned processes, i.e.,the simultaneous presence of the FAC and the TLE field. There is evidence that except for periods of moderate geomagnetic activity, the observed values of the field-aligned currents fall in the sub-threshold domain for the collisional EIC and IA instabilities [Fejer et al., 1984; Chaturvedi et al., 1987]. Also, there are several suggestions that the observations indicate the presence of transverse electric fields in the auroral regions [Fejer et al., 1984; Basu et al., 1984; 1985; Prikryl et al., 1986]. We therefore investigate the role of the TLE field on the current driven ion modes.

3. NUMERICAL RESULTS

We proceed to evaluate the nonlocal dispersion relation (9). We consider ion and electron temperatures to be equal ($\tau = 1$). Other typical parameters used are $\tilde{\nu}_e = \nu_e/\Omega_i = 12$. $\tilde{\nu}_i = \nu_i/\Omega_i = 0.033$, $\varepsilon = 0.1$ and $u = k_\parallel/k_\perp = 0.15$. We study an O^+ ion-plasma system i.e., $\mu = m_i/m_e = 29392$.

Figure (2) shows the real and the imaginary parts of the frequency (ω_r and γ) as a function of $b(= k_\perp^2\rho_i^2/2)$ for $\bar{V}_0=V_0/v_i=0$ and $\bar{V}_d=V_d/v_i=30$. The mode is stable for the $k_\perp$ domain of interest. The real frequency shows the expected weak-dependence on b. This is in agreement with the previous studies which suggest a higher threshold value of V_d for EIC wave excitation (Satyanarayana et al. [1985], Providakes et al. [1985]).

Next we consider $V_d = 0$ and let $\bar{V}_0 = -2.8$, $\nu_e = 0$, $\nu_i = 0$. From figure (3) we see that the real frequency of the mode has a roughly linear dependence on b. We find that the mode is stable for the b-domain which we have scanned and which is of interest to us. Thus, for $\bar{V}_d = 30$, $\bar{V}_0 = -2.8$, $u = 0.15$, $\bar{\nu}_e = 12$, $\bar{\nu}_i = 0.033$, the nonlocal electrostatic instability discussed by Ganguli et al. [1985] and the collisional current driven EIC instability are both stable individually.

Now we combine the two drifts ($\bar{V}_d$ and $\bar{V}_0$) for the values given above and solve (9) numerically. The results (ω_r and γ plotted vs. b) are shown in figure 4. A comparison with figs. (2) - (3) reveals that the mode frequency follows the approximate pattern of the nonlocal electrostatic instability (fig. 3) but the growth rate is positive. Thus, we find that in presence of a parallel electron drift (V_d), the nonlocal electrostatic instability exhibits growth, even in the presence of collisions. Based upon this result, we suggest that in the collisional low-altitude auroral ionosphere, the observed low frequency plasma waves may have been excited due to the simultaneous presence of both the transverse electric field and the parallel current. A similar conclusion for the collisionless (high-altitude) case can also be drawn, indicating that excitation of the ion-modes jointly by the parallel current and the transverse electric field is possible for sub-threshold electron current.

We find that the effects of finite channel-width (L_c) on the nonlocal ion instability are relatively small if $L_c \gtrsim L_v$. In figs. (3) - (4), we have assumed $L_c > L_v$. For comparison, we plot γ vs. b in fig. 4 for the case $L_c = L_v$ (dashed curve). We see that the growth rate in this case is of the same order as before ($L_c > L_v$) though slightly larger. Qualitatively the reason for the relatively smaller influence of finite L_c on the nonlocal ion instability in cases when $L_c \gtrsim L_v$ is that the wave packet (localized around the electric field) samples the region of near peak current in space.

The value of the $|\bar{V}_0| = 2.8$ used in the numerical computations above is larger than the typical observed value of $|\bar{V}_0| \sim 0.5$. In figure (5) we now consider $\bar{V}_0 = -0.5$ and $\bar{V}_d = 30$ and 25 with $u = 0.15$ and 0.17, respectively. The rest of the parameters remain unchanged from the figure (4). Now we see a rather coherent electrostatic wave growth around the ion cyclotron frequency for sub-critical values of $\bar{V}_d$.

4. DISCUSSION

We have shown in this article that the simultaneous existence of a localized transverse electric field and a parallel current can excite the oblique ion modes even though the electric field and the current values are separately stable. The parameters we considered are typical to the low-altitude auroral ionosphere (the upper E-region). In this region various experiments have indicated observations of EIC or EIC-like ion-modes. These observations are frequently attributed to a field-aligned current-driven EIC generation, but often the current is below the threshold value required for excitation [see, e.g., Fejer et al., 1984]. And the frequency of the modes may also display variations; it may be equal to the ion-cyclotron frequency or sometimes different from it [Prikryl et al., 1987]. In absence of detailed data on the ambient parameters, it is not possible to obtain close comparisons with the observations. However, for the parameters we have considered, it appears that the excitation of the transverse electrostatic modes by a combination of a TLE field and a parallel FAC can be a possibility. The parallel currents (corresponding to tens of $\mu A/m^2$, i.e., $\bar{V}_d \sim 30$) and the transverse electric fields (corresponding to 100 mv/m, i.e., $|\bar{V}_0| \sim 0.5$) correspond to the typical values that are believed to have been observed in the regions of auroral wave activity. Further, the range of unstable mode frequencies varies from below Ω_i to values greater than Ω_i and may have relevance to the auroral situations where the observed wave frequencies sometimes are different from the ion-cyclotron frequency.

The mechanism of mode excitation in the combined presence of V_0 and V_d is of interest to other situations as well. For example, at higher auroral altitudes, the observations of EIC-like modes (and lower hybrid (LH)-like modes) have been made where the TLE fields may have been non-negligible [Kintner et al., 1979]. We are presently conducting a parameter study for this case. In addition, the profile of electric field chosen by us in this paper is an idealization. Preliminary investigations with a smooth profile suggest that our results are not severely modified. Detailed results will be provided in a forthcoming publication.

In conclusion, we have shown that the sub-threshold parallel currents and stable transverse electric fields may combine to result in the growth of electrostatic ion modes in a collisional plasma. We have applied our results to the lower altitude auroral ionosphere and find that reasonable

values of parallel currents and transverse fields may result in the ion mode excitation under relatively less severe conditions of geomagnetic activity. Detailed results including the collisionless case applicable to higher altitudes will be presented in a future publication.

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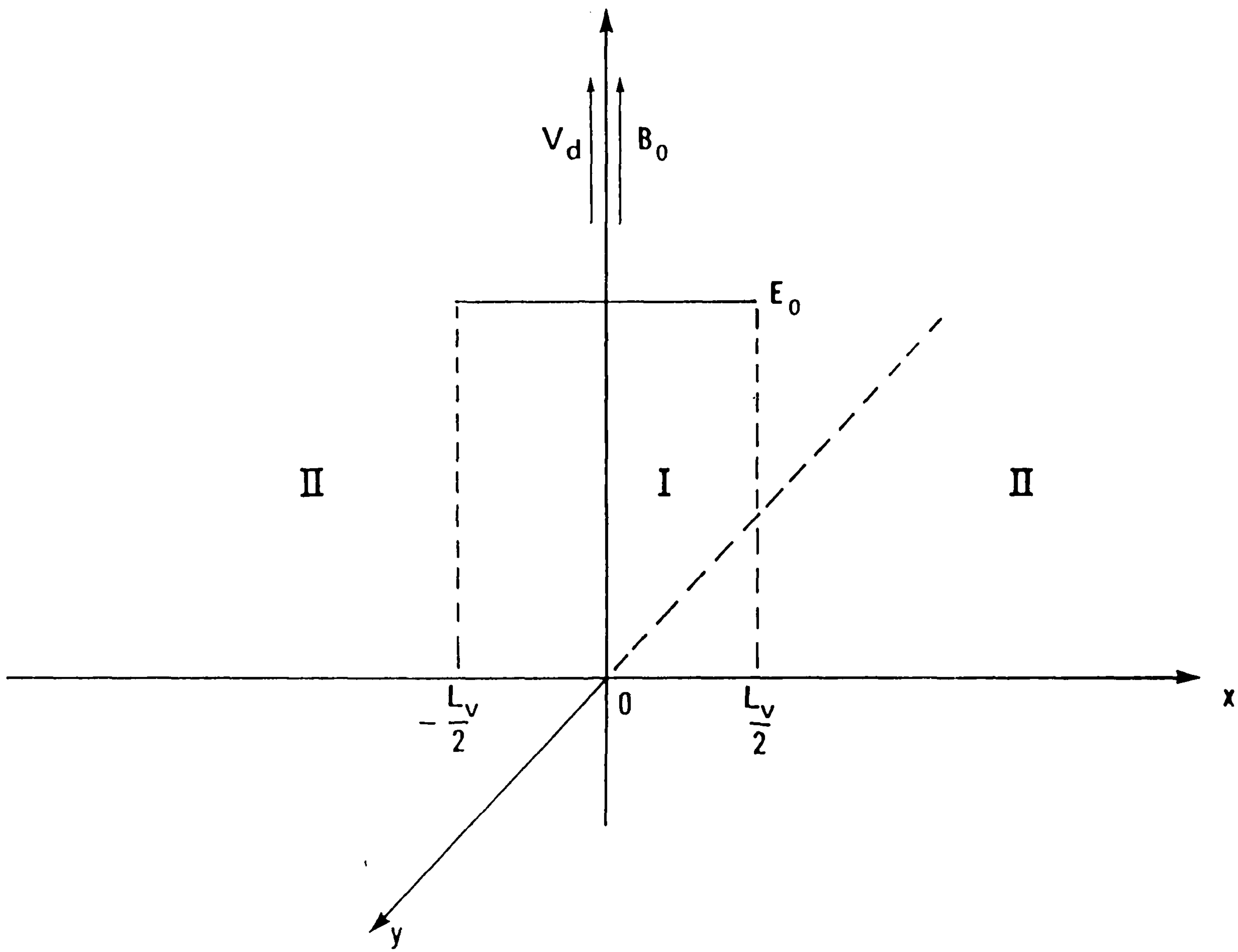

Figure (1) A sketch of the equilibrium configuration.

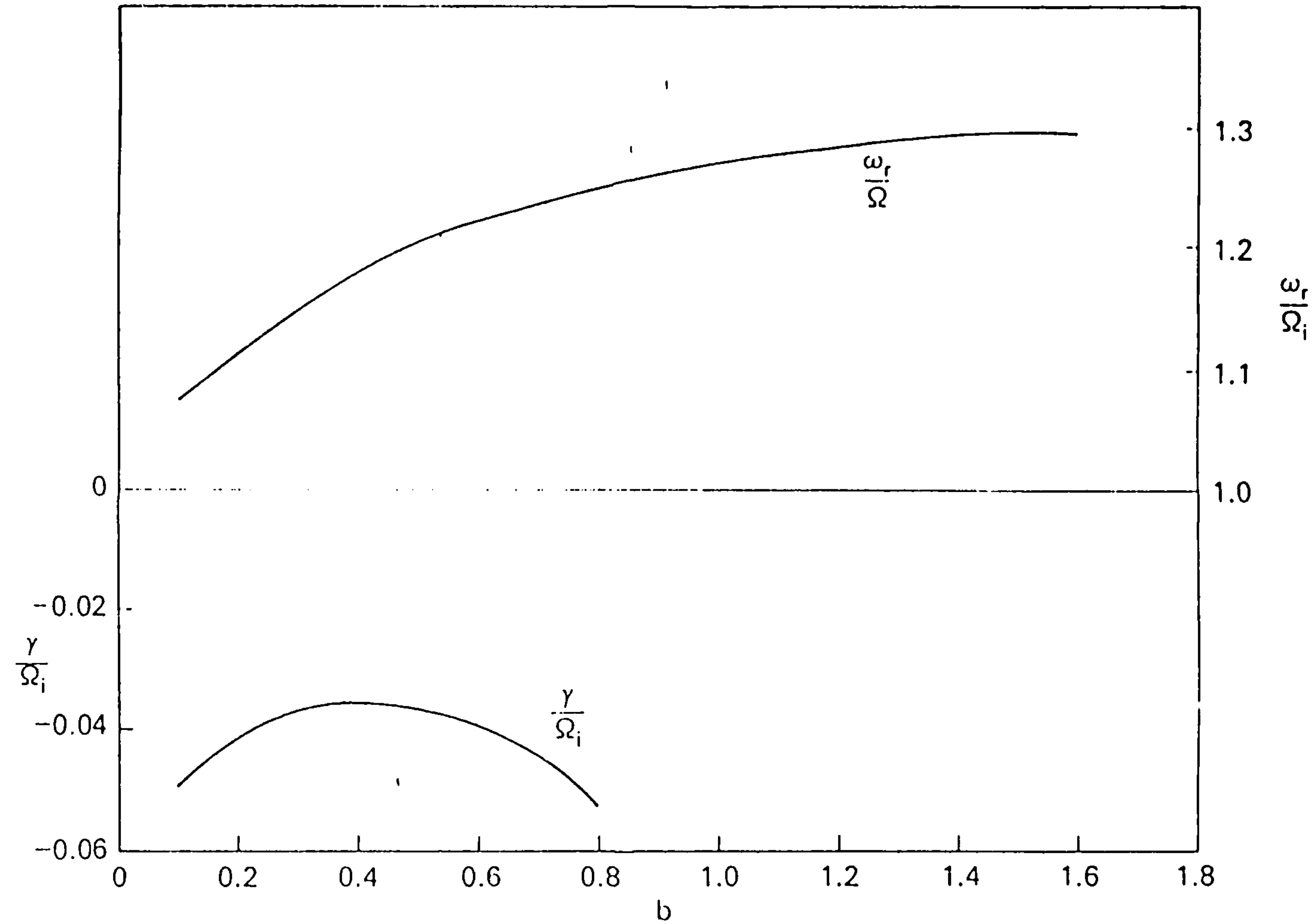

Figure (2) The growth rates and the real frequency of the collisional current driven ion cyclotron waves plotted as a function of $b(= k_y^2 \rho_i^2/2)$. Here $\tau = 1$, $\bar{\nu}_e = 12$, $\bar{\nu}_i = 0.0333$, $\varepsilon = 0.1$, $u = 0.15$, $\mu = 29392$, $\bar{V}_0 = 0$, and $\bar{V}_d = 30$.

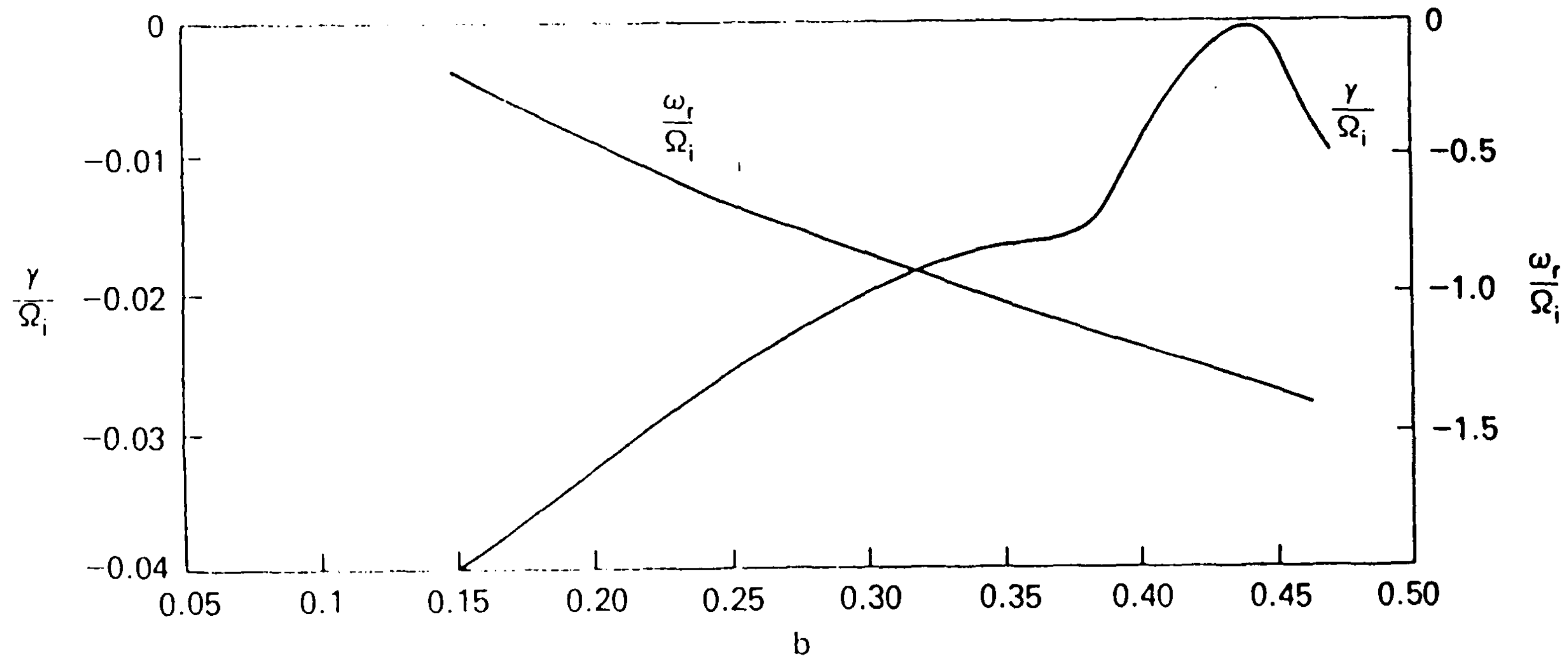

Figure (3) The growth rate and the real frequency of the electrostatic ion modes due to a transverse electric field. Here $\bar{V}_0$ = -2.8, $\bar{\nu}_e = \bar{\nu}_i = 0$, $\bar{V}_d = 0$ and rest of the parameters are identical to figure (2).

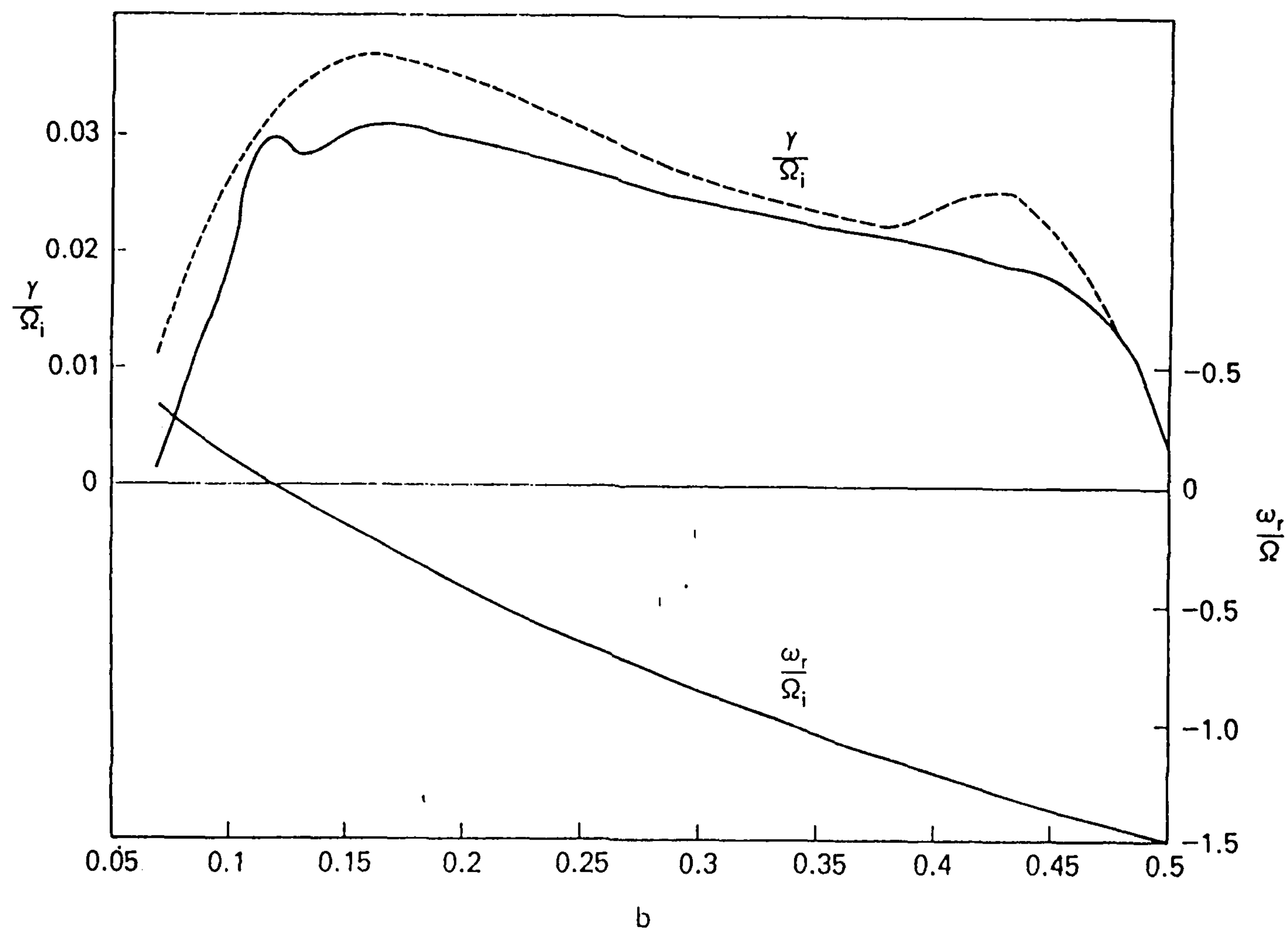

Figure (4) A plot similar to the figures (2) and (3). Here $\bar{V}_0 = -2.8$ and $\bar{V}_d = 30$ and the rest of the parameters are identical to figure (2). The solid line refers to the case where $L_c > L_v$ while the dashed line refers to the case where $L_c = L_v$.

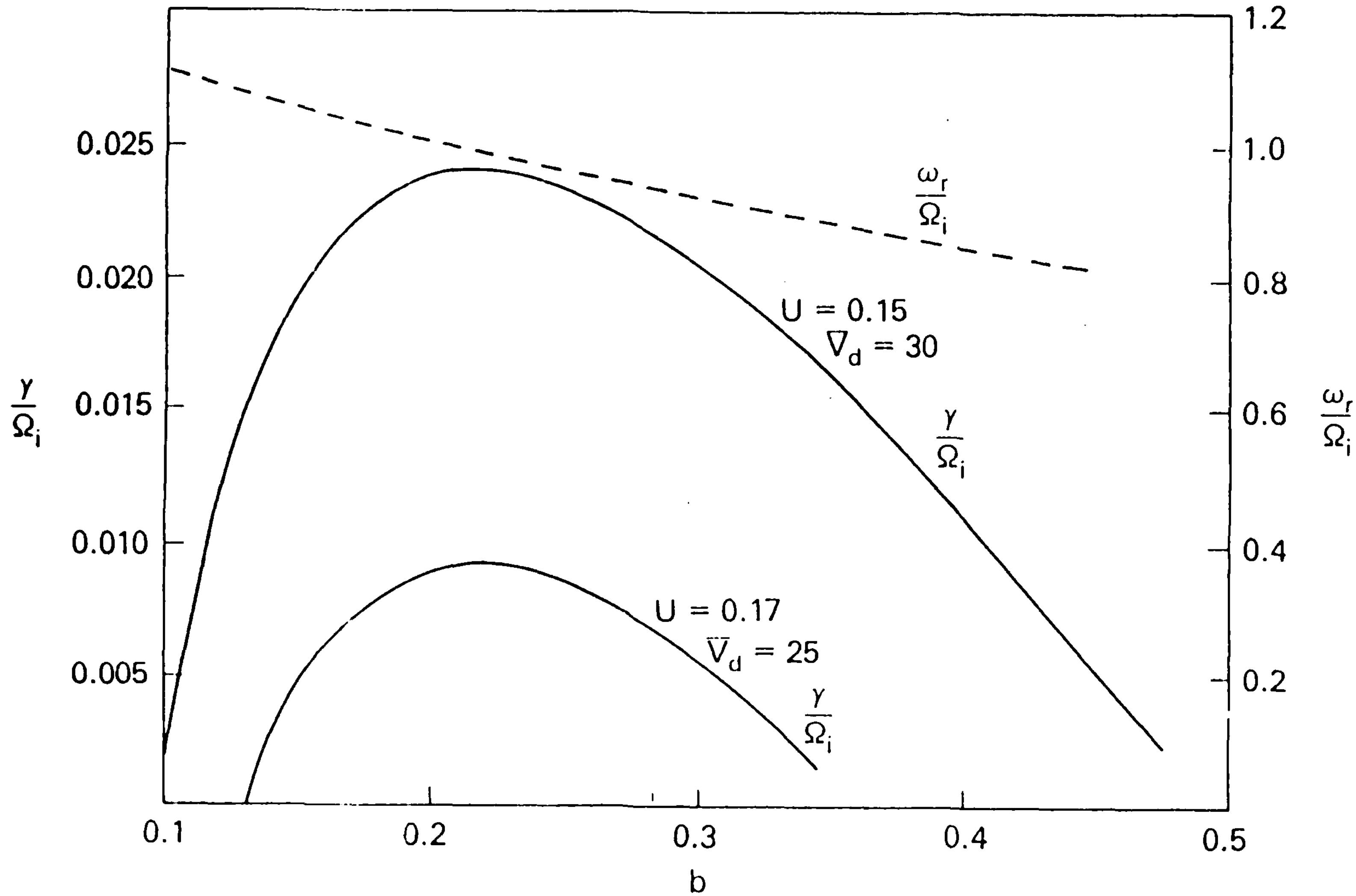

Figure (5) A plot similar to the figure (4). Here $\bar{V}_0 = -0.5$ and $\bar{V}_d = 30$ and 25 with the corresponding values of $u = 0.15$ and 0.17. The rest of the parameters are similar to the figure (2).

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